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Stormflow Production in a Headwater Basin Swamp

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Summer stormflow from a 1.57 km^2 headwater basin in southern Ontario, Canada, which contained a 0.31 km^2 valley-bottom, treed spring-fed swamp, was examined in 1987 and 1988. A large and annually constant groundwater flux emerged in the swamp, producing permanent saturated areas and a series of surface streamlets. The streamlets play a significant role in the production of an overland flow component of storm runoff. Stormflow volume produced by the basin was very small (runoff coefficients less than 0.01), but because of the well developed surface 'streamlet' system stormflow response and recession were rapid. Stormflow yield was equivalent to the depth of precipitation incident on the surface streamlets and stormflow volume was directly proportional to the volume of rain, indicating the size of the saturated zone was constant and not influenced by the storm rainfall. There was no evidence of groundwater being a major contributor to storm runoff. However, because groundwater controls the development of the surface streamlets and swamp saturation, seasonal groundwater hydrology and storm surface hydrology are inseparable.

Introduction

It is common in humid regions with deep deposits leftover from the last glaciation, such as in Eastern Canada and North Eastern United States, that streams originate in groundwater discharge areas. These headwater basins often contain small treed spring-fed swamps (National Wetlands Working Group 1988) where saturation is maintained by a large influx of groundwater (Roulet 1990a). The large groundwater flux is important in sustaining stream baseflow, the development of a swamp's morphology, and maintaining swamp saturation. Because these swamps are located adjacent to streams they are important in biogeochemical transformation of the emerging groundwater (Hill and Warwick 1987, Hill 1990a). Although these small spring-fed headwater swamps are a common feature of the regional landscape (*eg*. Carter and Novitzki 1988) there has been little work done on the production of storm runoff from these systems. The objective of this paper is to examine the stormflow characteristics and mechanisms of stormflow production from summer rain events in a headwater basin which contained such a swamp.

Most field studies of the mechanisms of runoff production in humid regions (see Dunne 1978 and Ward 1984 for reviews) have been conducted on headwater basins or hillslopes where the groundwater flux was small or absent most of the year. The characteristics of storm response are controlled by the dynamics of stream-side saturation zones (variable source areas), the conductivity and hydraulic gradients on adjacent hillslopes adjacent to streams (Dunne 1978), the extent of macroporosity (Beven and Germann 1982), and groundwater mounding in the area adjacent to the stream (*eg*. Gillham 1984). In basins that contain swamps, saturated overland flow tends to dominate (Taylor 1982). However, O'Brien (1980) found groundwater accounted for up to 90 % of the stormflow generated from a swamp that received a very large groundwater input. Most studies of stormflow from swamps (see Carter 1986 for review) show that the presence of a swamp attenuates peak flows and elongates recessions, but does not reduce stormflow volumes because the storage capacity is usually limited (Roulet 1990b). It was hypothesized that valley bottom swamps would act as a source area for overland flow and stormflow yield would equal or exeed the depth of rainfall incident on the swamp. A combined hydrometric and geochemical approach was originally planned for this research, but Hill (1990a, b) found two geochemical distinct sources of groundwater to the swamp which precluded the use of a simple two compartment mixing model. Therefore, the results discussed in this paper are based on hydrometric measurements only.

Study Site

The study basin is located in the headwater region of the Duffin Creek drainage basin, Southern Ontario, Canada (43° 47′ N, 79° 15′ W: see Roulet 1990a Fig. 1 for location). The basin area is 1.57 km^2: 0.031 km^2 is occupied by a valley bottom treed swamp (Fig. 1). Two first order streams, called 1N and 2N, rise in the basin and join to form a second order stream, 2M, that leads to the outlet. The slopes of the basin are relatively steep and relief ranges from 280 m at the outlet to 340 m on the northern perimeter of the basin (Fig. 1). Soils of the upland hillslopes and the swamp are grey-brown luvisols and 1.5 m of peaty histosols underlain by grey sands

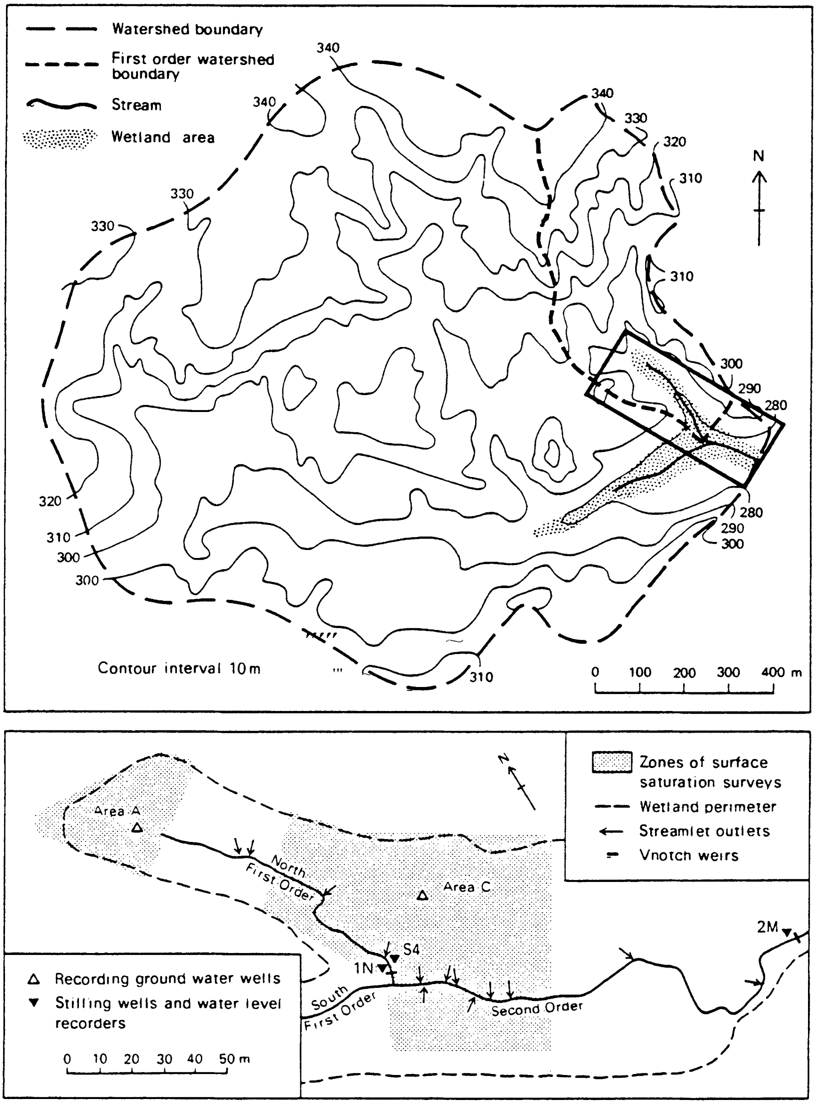

Fig. 1. Upper: The topography of the study basin and the location of the treed spring-fed swamp in the valley bottom. The enclosed rectangle indicates the location of the enlarged are display below. Lower: Location of the water level recording sites and the area of the surface saturation survey.

and fluvio-glacial deposits (Hill and Warwick 1987). Upland vegetation comprises grasses in fallow fields and stands of beech and maple, while the swamp forest comprises hemlock and cedar with an understory of shrubs and seedlings.

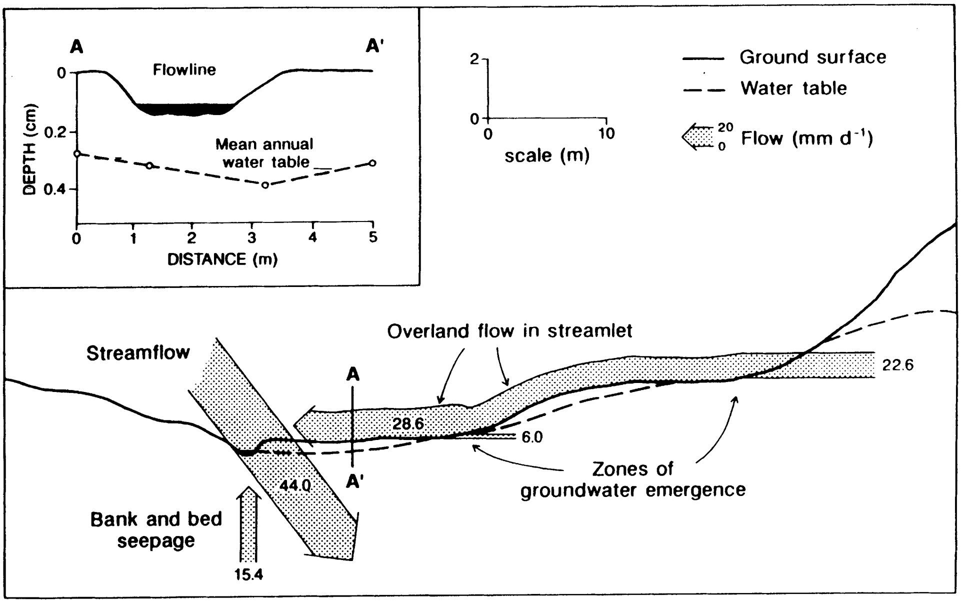

Fig. 2. A schematic diagram showing the routing of groundwater over the swamp to the central stream. The values indicate the mean annual flow by each route (mm) (Roulet 1990a). The main transport route is by the surface streamlets. The insert shows the mean annual water table elevation beneath one of the thirteen streamlets at location A – A′.

The hydrogeology, hydrogeochemistry and groundwater of the Duffin Creek basin were examined by Sibul *et al.* (1977) and Howard and Beck (1986). Roulet (1990a) described the link between the seasonal groundwater and surface hydrology of the study basin, which is located in a discharge zone of the Oak Ridges aquifer.

The basin swamp receives a large and constant groundwater input of greater than 45 mm d^{-1} (Roulet 1990a), which based on the geochemical analysis of Hill (1990a, b) is a mix of local and regional groundwater. The groundwater input has led to the development of 13 surface 'streamlets' that cross the swamp from points of groundwater emergence to the stream (the streamlet outlet points are shown in Fig. 1). These streamlets are between 10 and 200 cm wide and are generally less than 5 cm deep. They range in length from 20 to 50 m depending on the width of the swamp (Fig. 2). The groundwater table intersects the streamlets only where the upwelling groundwater reaches the swamp surface and for most of the streamlets' course they are separated from the water table by more than 20 cm (Fig. 2). Approximately 60 % of the groundwater emerging in the swamp is transported by streamlets. The remaining groundwater enters the stream as seepage.

Methods

The study of storm runoff production was undertaken in the 1N and 2M portion of the basin (Fig. 1). A 53° thin-plate V notch weir was installed at the basin outlet in April 1987. Additional V notch weirs, 45° and 22°, were installed at the outlets of 1N and streamlet S4. Water level was recorded continuously behind all weirs. Water table elevation was recorded at two sites in the swamp: one mid-way up the swamp (Area C) and the other in the saturated area near the origin of stream 1N (Area A). Basin discharge was measured between April 1987 and October 1988 while all other sites were monitored in 1987 only. Rainfall was measured in 0.2 mm increments using a tipping bucket raingauge and 10 non-recording raingauges distributed throughout the basin were used to assess the volume of rainfall.

The areal extent of the swamp was surveyed in 1987 and a total of 43 % of the 1N and 2M portions of the basin were measured for surface saturation (Area A and C in Fig. 1). After this survey, the width of several saturated patches were monitored every two weeks for changes in surface area.

Results

Characteristics of outlet and 1N basin storm discharge were analyzed for 32 rainstorms that occurred between May 1987 and November 1988. The storms used in this analysis ranged from 1.3 mm to 28.1 mm (Fig. 3). The response from two storms will be discusses in detail to illustrate the major flow paths and means of stormflow production.

Stormflow Characteristics

A runoff coefficient, defined as Q_s / P A, where Q_s (m^3 t^{-1}) is the stormflow intergrated over the period t which is from the time of rise to the time when

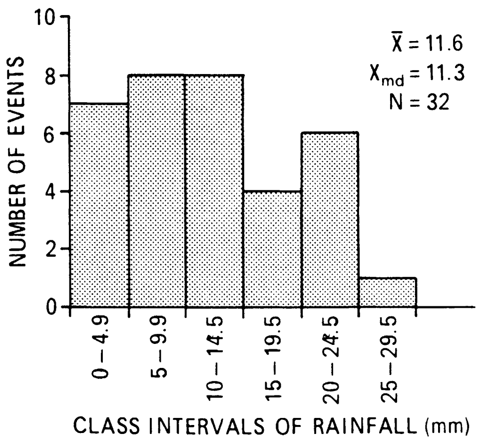

Fig. 3. Class size distribution for the 32 storms used in the characterization of basin stormflow.

streamflow returned to within 2 % of baseflow, and P (m storm^{-1}) is the depth of precipitation over the study area A (m^2), was computed for each storm. The volume of stormflow was derived by integrating the area under the hydrograph above the baseflow before and after the storm event. Stormflow is easily distinguished from baseflow, but this analysis does not imply any partitioning between sources of stormflow (*ie* old *vs* event water). Runoff coefficients were determined using two areas: the entire basin (1.57 km^2) and the basin swamp (0.031 km^2). The recession in stormflow was described by $Q_t = Q_0 K^t$, where Q_0 and Q_t are the discharge at the time of peak flow and t, and K is the recession coefficient (hr). The recession was considered completed when flow had returned to within 2 % of baseflow.

Fig. 4 illustrates the responsiveness of the basin to rainfall. The summer hydrographs from 1987 and 1988 indicate short lag times and recessions and relatively large peakflows (Table 1).

Mean basin runoff coefficients were small, less than 1 % of storm rainfall. Since it was hypothesized that the entire swamp would act as a source area, runoff coefficients were also computed using the area of the swamp. Storm runoff was equivalent to, on average, 31 % of the rainfall incident on the swamp. The swamp portion of the 1N sub-basin produced only marginally higher yields indicating that the magnitude of stormflow varied little between 1N and the larger study basin swamp. Storm runoff from the study basin was proportional to the magnitude of the rain event (Fig. 5). The slope of the relationship between depth of rainfall and storm runoff from the study basin and 1N swamp was 0.33 and 0.31 respectively. The areal survey revealed that 33 % and 24 % of the surface in Area C and Area A of the swamp were saturated. The extent of the saturated areas did not vary over the study.

Even though the stormflow hydrographs were very peaked, areal weighted peak runoff was very small: mean of 0.1 mm hr^{-1} based on the basin area, and 4.1 mm

Table 1 – Stormflow Characteristics

	Runoff Coefficients			Peak Runoff	Response Time		Recession Coefficient[3]	
	Basin	Swamp	1N Swamp	(mm hr^{-1})	T_r[1]	L_p[2] (hours)	K_2	K_n (hours)
Mean	0.008	0.31	0.37	0.08	2.7	<0.5	0.56	0.70
SD	0.003	0.13	0.16	–	1.9	–	0.18	0.08
Maximum	0.013	0.57	0.68	0.04	8.5	–	0.98	0.86
Minimum	0.001	0.05	0.17	0.17	0.5	–	0.12	0.51
N	25	25	8	32	32	16		31

1. Time of rise (hrs)
2. Time from pulse of intense rainfall to peak discharge (to correspond with Dunne 1978)
3. K_2 represents the recession coefficient calculated over the first 2 hours after peak flow, while K_n was calculated over the entire recession period (defined in text)

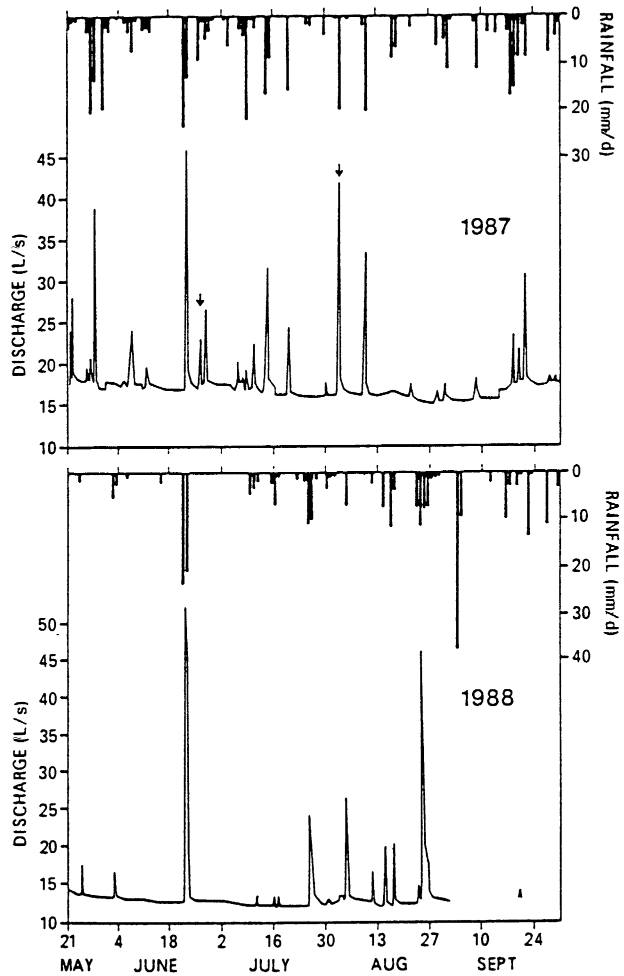

Fig. 4. Summer outlet (2M) streamflow hydrograph and rainfall for 1987 (upper box) and 1988 (lower box). The arrows on the 1987 hydrograph indicate the storms shown in detail in Figs. 6 and 7.

hr^{-1} based on the area of the swamp. Outlet response to rainfall was very rapid (less than 30 minutes) and therefore difficult to quantify accurately. The duration of recession period was relatively short (Table 1). The recession in stormflow was rapid in the first 2 hours after peak flow, but became more elongated as the time interval since peak flow increased. The mean recession coefficients (hrs) for the periods between peak flow and 2 hours, 2 and 4 hours, and 6 and 10 hours after peak flow were respectively 0.56, 0.73, and 0.75 indicating a non-linear recession. The slope of the recession curves were independent of the magnitude of the rain event ($p = 0.01$).

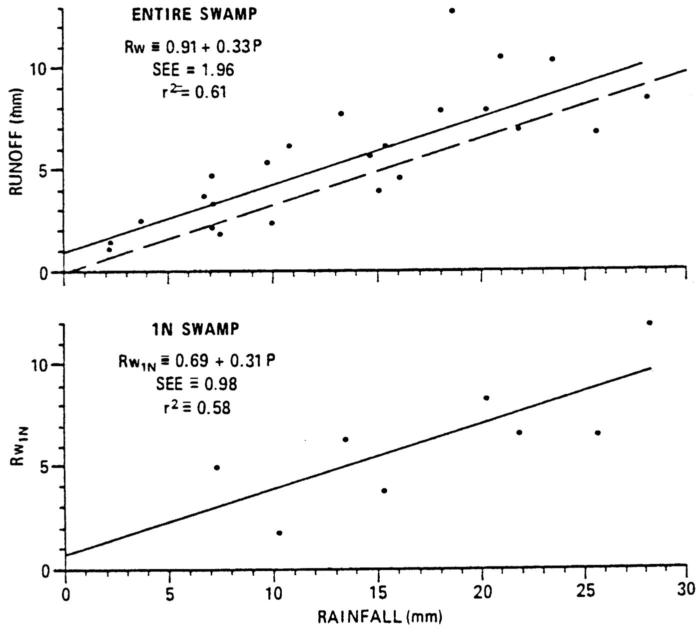

Fig. 5. Basin swamp, 1987 and 1988, and 1N swamp, 1987, stormflow runoff versus storm precipitation. *R, P, SEE* and r^2 signify, respectively, runoff and precipitation (mm $storm^{-1}$), standard error of the estimate (mm $storm^{-1}$) of *R* using the regression equation, and the coefficient of explanation.

Stormflow Generation

Of 19 storms from 1987, 8 were analyzed for the mechanisms of storm response. Two storms, one representing the mean and median rainfall (June 26: 12.2 mm, ranks 17th out of 32 storms, see Fig. 3) and one representing a larger event (August 2: 22.8 mm, ranks 30th out of 32 storms) will be discussed below. Both storms were single peaked, but of different duration: 5 hours on June 26 compared to 9 hours on August 2, with peak intensities of 5.8 and 8.7 mm hr^{-1} respectively.

Eighty-three per cent of the storm rainfall occurred in the first 2 hours of the June 26 event (Fig. 6). Discharge increased rapidly in the first order stream, 1N, compared with that at the basin outlet (2M). This rise cannot be attributed to streamlet discharge since the proportion of S4 to 1N discharge decreased by 7 % in the early part of the storm. Unlike most of the swamp, which has 11 well developed streamlets connecting points of groundwater seepage, the 1N swamp has numerous small saturated areas adjacent to stream 1N that generate flow rapidly, but only one well developed streamlet (S4). Also the initial rise in 1N discharge could not have been produced from Area A, the point of origin of stream 1N, since the water table rose to near-surface only after discharge at 1N, S4 and the basin outlet had

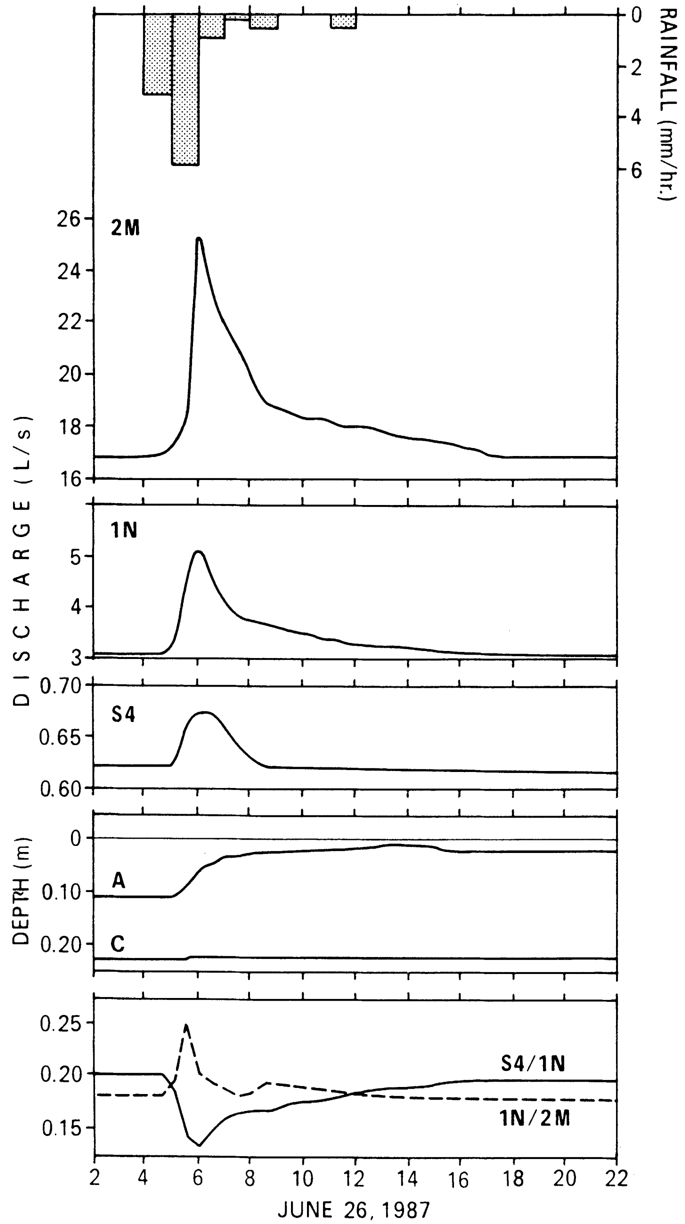

Fig. 6. The storm hydrographs for the basin, 1N, and 2M outlets, water table elevation relative to the ground surface for Areas A and C, and hourly rainfall distribution for June 26, 1987.

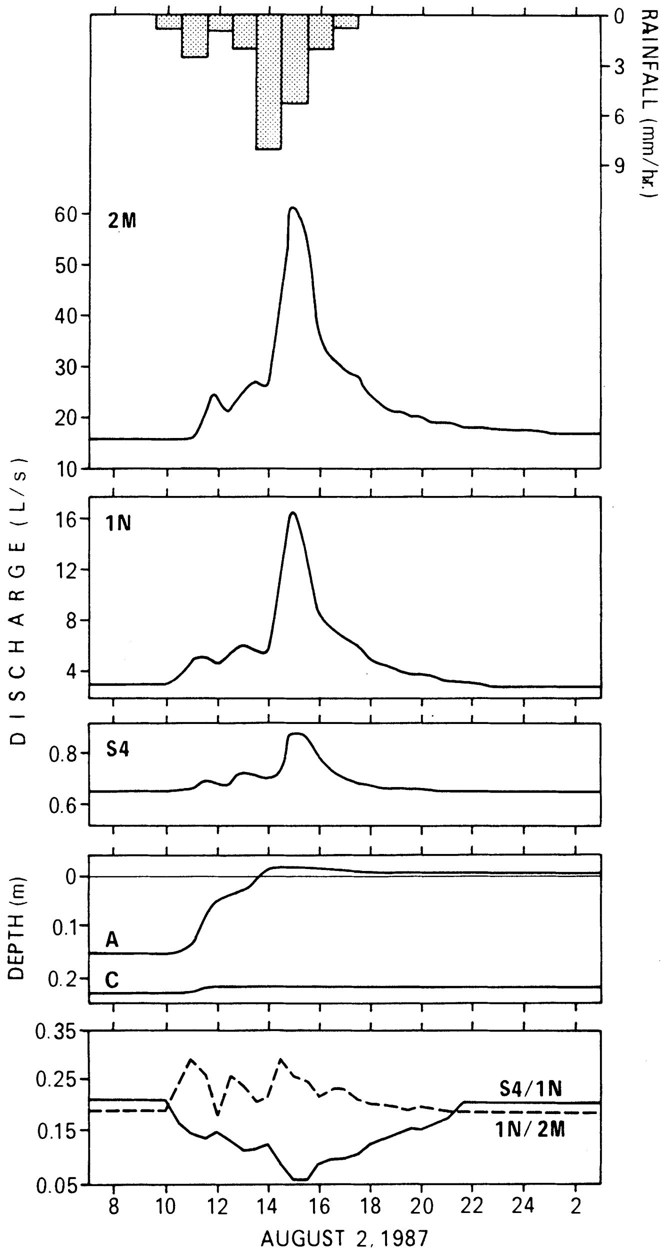

Fig. 7. The storm hydrographs for the basin, 1N, and 2M outlets, water table elevation relative to the ground surface for Areas A and C, and hourly rainfall distribution for August 2, 1987.

peaked. Peak basin discharge occurred less than one half hour after 1N peaked and coincided with peak discharge from S4. The water table in the main area of the swamp, Area C, changed little throughout the storm. Roulet (1990a) found that the water table in Area C was unaffected by rainfall and remained very constant throughout the thawed season indicating that there was no rapid percolation of event water to the water table at this point. S4 recession took less than 2 hours (*ie* flow returned to within 2 % of baseflow) and flow receded at 1N and the basin outlet in 10 and 12 hours respectively.

The August 2 storm was of a longer duration. Maximum rainfall occurred in the fifth hour after 35 % of the rain had fallen (Fig. 7). In contrast to the June 26 storm the water table in Area A rose above the ground surface before the maximum rainfall. Again discharge from 1N increased first, but in this storm the 1N discharge initially represented 31 % compared to 25 % on June 26. The proportion of S4 to 1N discharge was smaller in this storm: 16 % decrease on August 2 compared with only a 7 % decrease on June 26. Rainfall continued for 2 hours after the peak and the S4 recession was more elongated than June 26. The 1N and outlet recession were similar to the earlier event. The water table in Area C responded only slightly.

Discussion

A rapid but very short duration storm runoff response resulted in very small yields from the study basin. Response times were similar to basins dominated by overland flow, Horton or saturated, but the storm runoff coefficients were smaller than for basins dominated by subsurface stormflow (Table 2, compiled from Dunne 1978). The small stormflow volume resulted from a small contributing area relative to the size of the basin. Only a portion of the swamp acted as a source area. In contrast to the stormflow produced in the variable saturated swamp investigated by Taylor (1982), runoff from this headwater swamp was proportional to the depth of rainfall. The swamp examined by Taylor was connected in spring to a perched groundwater system, but when the groundwater table dropped, the area of saturation decreased and stormflow correspondingly decreased to the point where runoff was not generated in mid-summer rain events. The constancy of saturated area in the study basin is a result of the large and persistent groundwater input. Since rainfall represents an insignificant input (less than 7 %, Roulet 1990a) it has no effect on the areal extent of saturation. The only portion of the study basin that experienced variable saturation was the area adjacent to where the stream first rises. Downstream of this point the zones of groundwater emergence and streamlets comprise the saturated zones. The size of these saturated areas was very stable resulting in a 'constant' source area.

Table 2 – Summary of the data reviewed in Dunne (1978) for drainage basins of between 1 to 2 km^2

Runoff Mechanism	Runoff Coefficient	Runoff Peak ($cm\ hr^{-1}$)	Lag Time (hr)	Recession Coefficient (hr)
HOLF	0.2 -0.8	2-5	0.45	0.022-0.189
SSSF	0.0 -0.2	0.1	15-20	0.83-0.98
VSA	0.01-0.59	0.2	1.2	0.42-0.89

HOLF, SSSF, and VSA represent Horton overland flow, Subsurface stormflow, and Variable source area generated saturated overland flow, return flow and subsurface flow, respectively.

The runoff generation in the study swamp also contrasts with that observed in swamps that receive a large influx groundwater. O'Brien (1980) found groundwater was the principal source of stormflow from 2 Massachusetts swamps. Stream discharge and the swamp water table rose quickly in response to rain and receded over 3 to 4 days suggesting that this groundwater originated from the swamp itself. The swamps O'Brien examined, although geologically similar to the study swamp, were larger and represented a greater proportion of the basin (25 to 30 %). There are few other wetland hydrology studies that have been conducted on such groundwater connected wetlands, even though this wetland type is common in certain terrain and geology (Carter and Novitzki 1988, Whiteley and Irwin 1986). Stormflow from the study swamp was much smaller and the recessions much shorter than those observed in other temperate swamps in southern Ontario (Taylor 1982, Woo and Valverde 1981). The subsurface storage capacity of this headwater wetland appears to be larger than most wetlands, but Verry *et al.* (1989) showed that peatland storage in most non-groundwater peatlands is highly variable and as a consequence so is stormflow yield. Other swamps provide detention storage, resulting in the attenuation of peak flows and the elongation of the recession, but do not significantly reduce overall stormflow yield compared to non-wetland basins of a comparable size. The opposite stormflow characteristics were observed in this study.

The sequence of runoff generation illustrates a system that rapidly sheds storm runoff. Flow is first produced from the saturated areas adjacent to the first order stream, quickly followed by direct precipitation on the groundwater emergence which is conveyed by the 13 streamlets to the main stream. Using fluorescent dye (Roulet, unpublished data) and chloride (Hill and Warwick 1987) it was found that water in the streamlets took less than 30 minutes to traverse the swamp.

The results presented in this paper have important implications for headwater basin management, especially with respect to the rapid urban expansion threatening these basins in Southern Ontario. The results indicate that headwater swamps reduce the magnitude of storm runoff. The areal extent of the swamp corresponds to the zone where the groundwater table intersects the surface of the mineral substrate beneath the swamp. Current wetland evaluation and inventory systems (*eg* Ontario Ministry of Natural Resources 1984) are not broad enough in scope to include these small headwater swamps and consequently their significance is usually overlooked in the development review process.

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